

Real-Time Powertrain Development and Sizing for the RVLT Lift Plus Cruise Concept Vehicle

Dr. Peter Suh, Kyle Barnes, Curtis Hanson, Kurt Kloesel
NASA Armstrong Flight Research Center

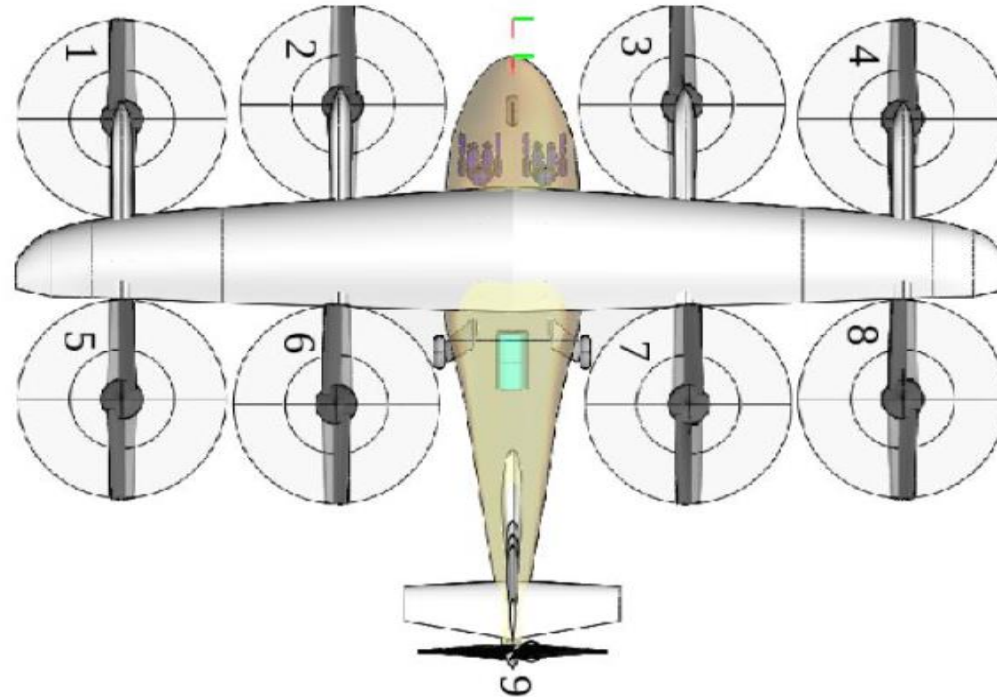
RVLT eVTOL Noise, Safety & Comfort Subproject

ACGSC Meeting #130
March 22-24, 2023

Vehicle Model

- Lift + Cruise design parameters from the NASA Design and Analysis of Rotorcraft (NDARC) tool [1]

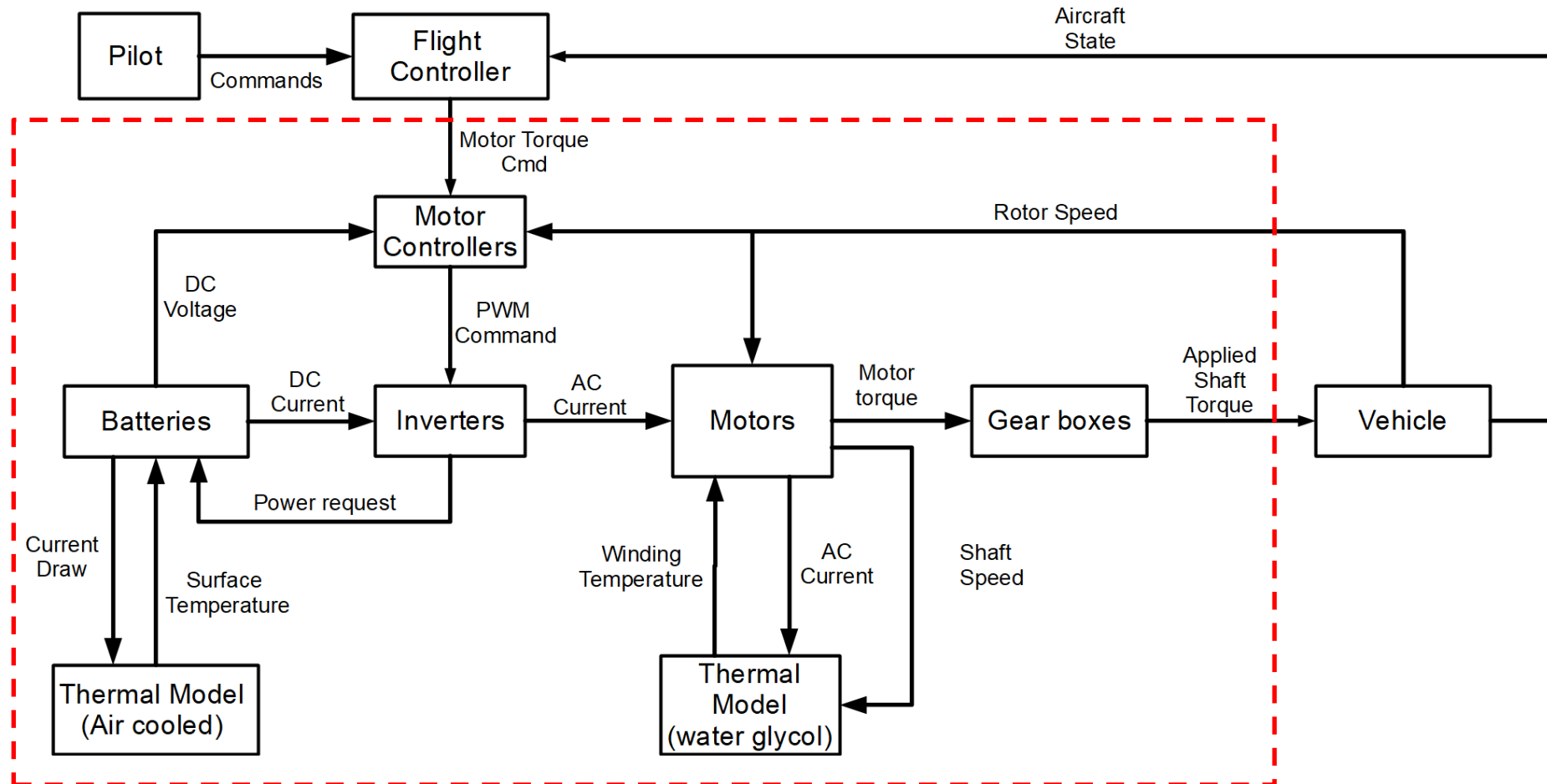
Lift + Cruise Vehicle and Motor Numbering



[1] Wayne J., NDARC – NASA Design and Analysis of Rotorcraft Theoretical Basis and Architecture, *Expanded paper from the American Helicopter Society Aeromechanics Specialists' Conference*, San Francisco, CA, Jan 20-22, 2010.

Lift + Cruise Simulation and Powertrain Architecture

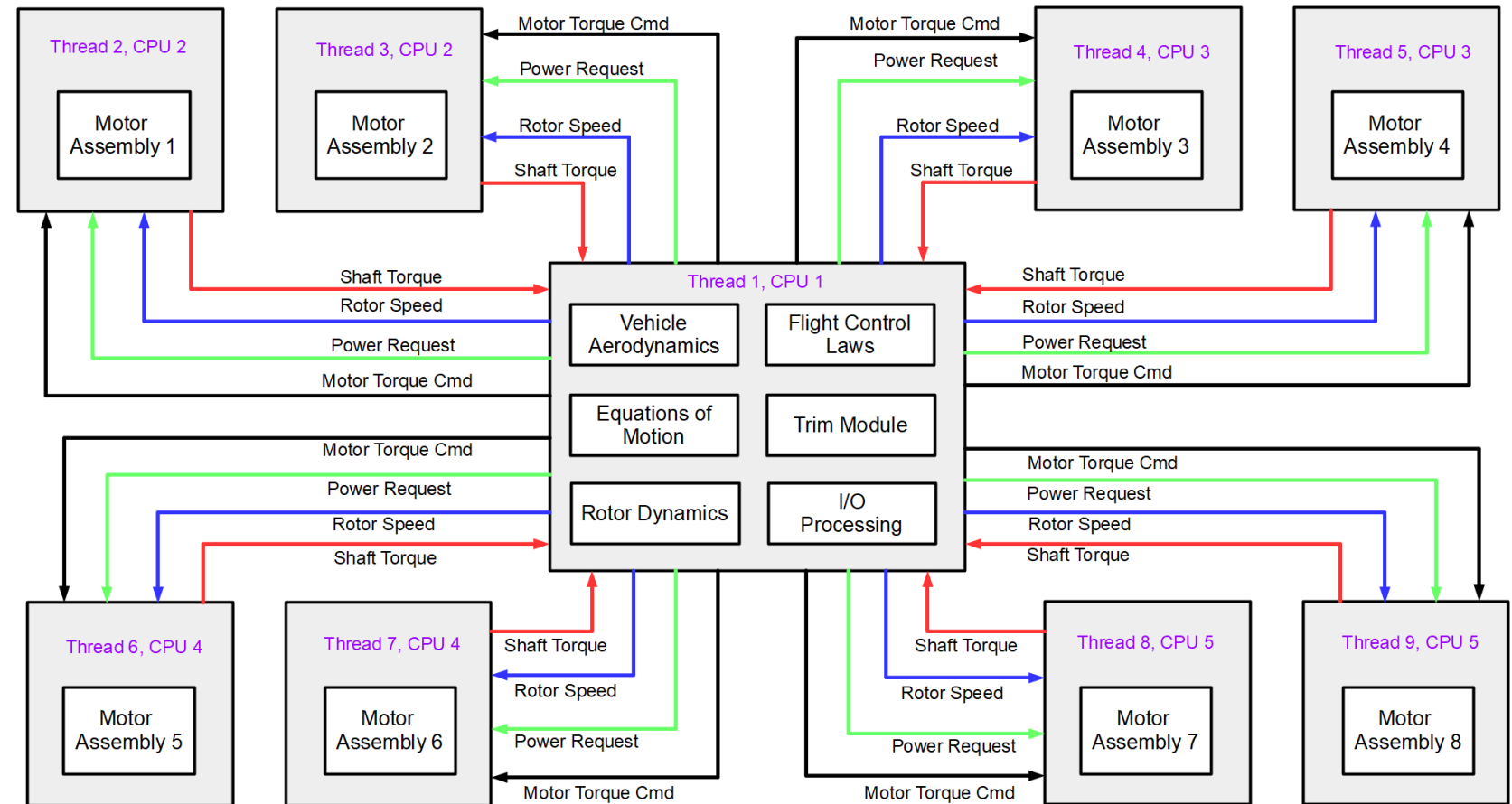
- Vehicle simulation interfaced with a powertrain architecture to assess the impact of the powertrain on pilot handling quality ratings



Powertrain Computational Architecture

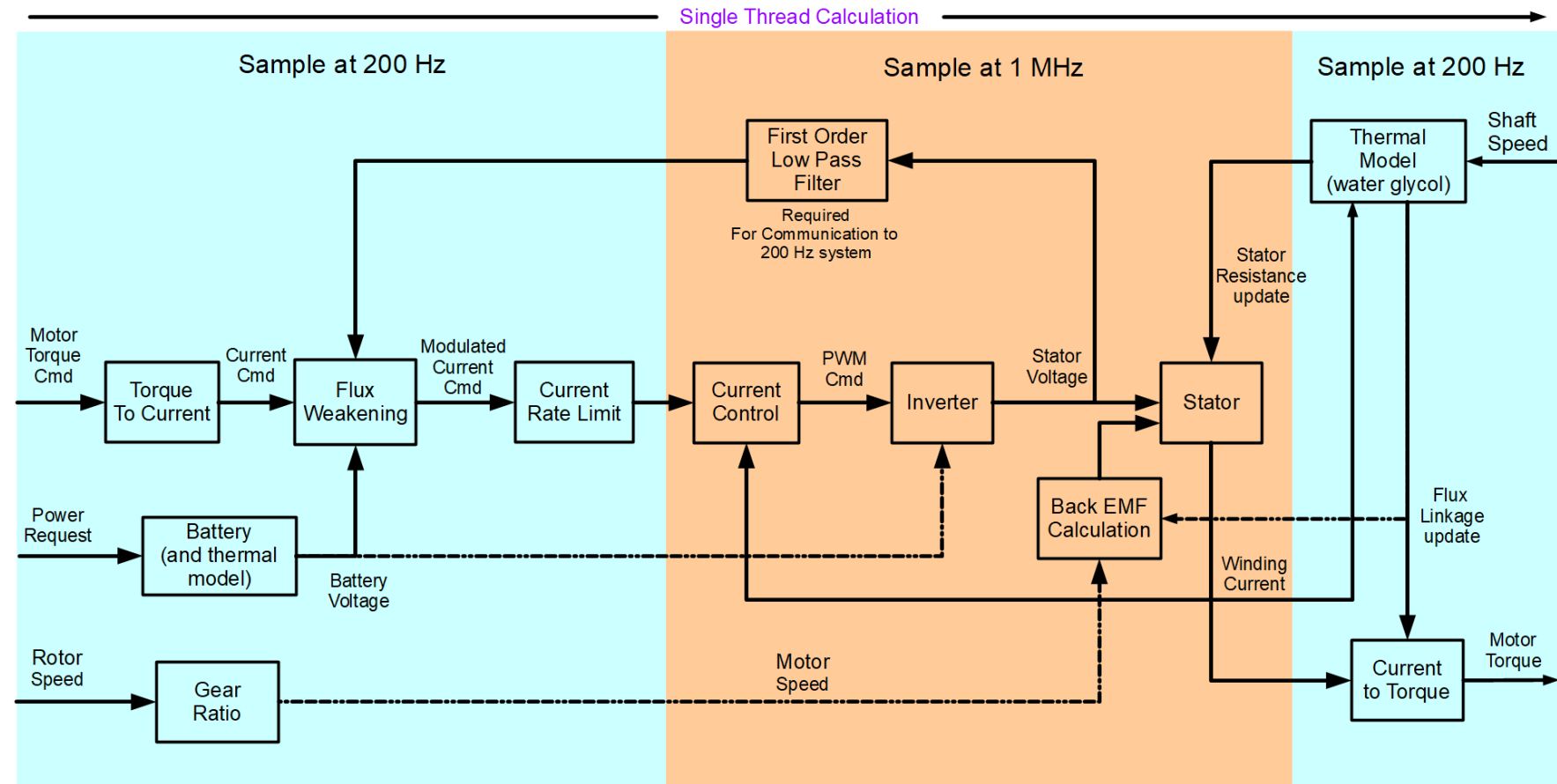
- The VMS requires a real time powertrain architecture
- All motor assemblies on separate threads
 - Each took up 40% of thread processing capability
- Vehicle model on its own thread

Vehicle and Powertrain Computational Architecture used in the VMS



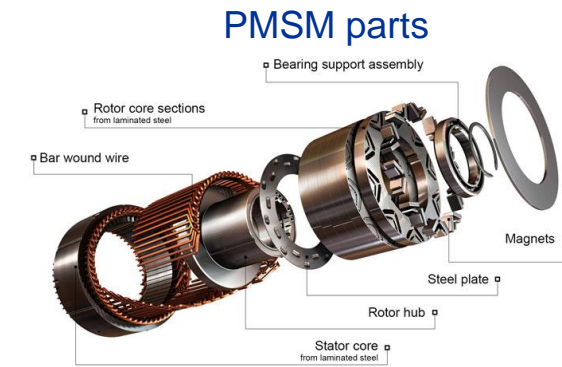
Powertrain for Real Time Operations

- Various powertrain subsystems had to be sampled at 1 MHz
 - Primarily due to high speed current dynamics
- Slower subsystems were run at 200 Hz
- A filter required to interface the 200 Hz system with the 1 MHz system for flux weakening control



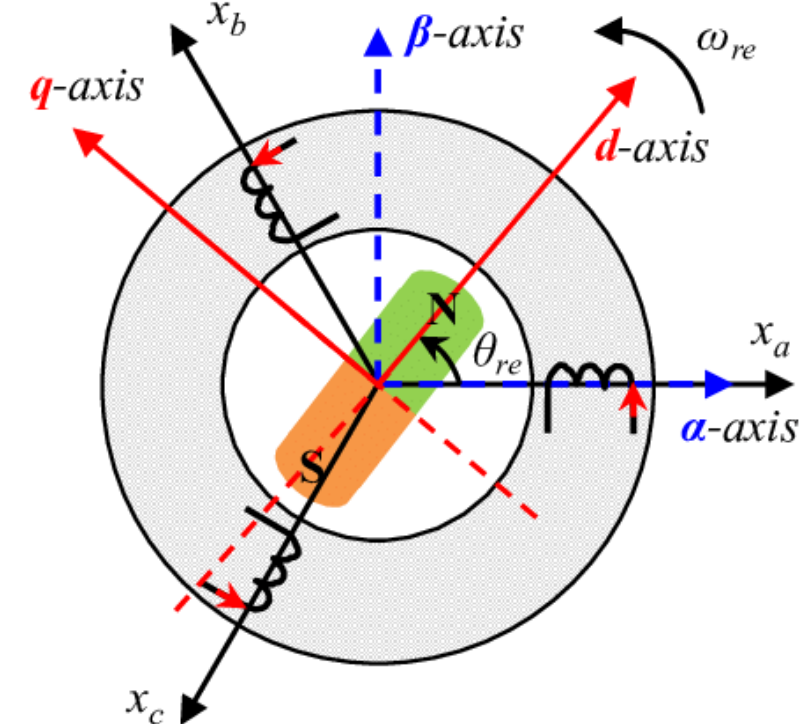
Review of PMSM Control Axes

- Permanent Magnet Synchronous Motor (PMSM) [1] selected for motor architecture
 - Advantages over other motors in efficiency, power density, size and weight
- Three frames typically relevant in control design
 - Three-phase fixed abc frame defined by winding locations on the stator
 - Two-phase fixed alpha-beta frame
 - Two-phase (Q-D) rotating direct-quadrature frame of the rotor
- Field oriented control (FOC)
 - Requires at least two frame transformations
 - Park and Clarke [2]



<https://en.engineering-solutions.ru/motorcontrol/pmsm/>

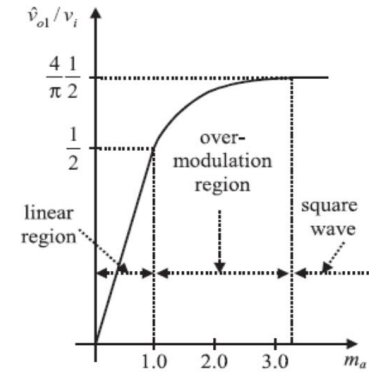
Three frames used to analyze PMSM



[1] Krishnan, R., "Electric Motor Drives Modeling, Analysis and Control, Prentice Hall, Hoboken, New Jersey, 2001

[2] Wu, Bin et al., Power Conversion and Control of Wind Energy Systems, John Wiley & Sons Inc., Piscataway, New Jersey, 2011

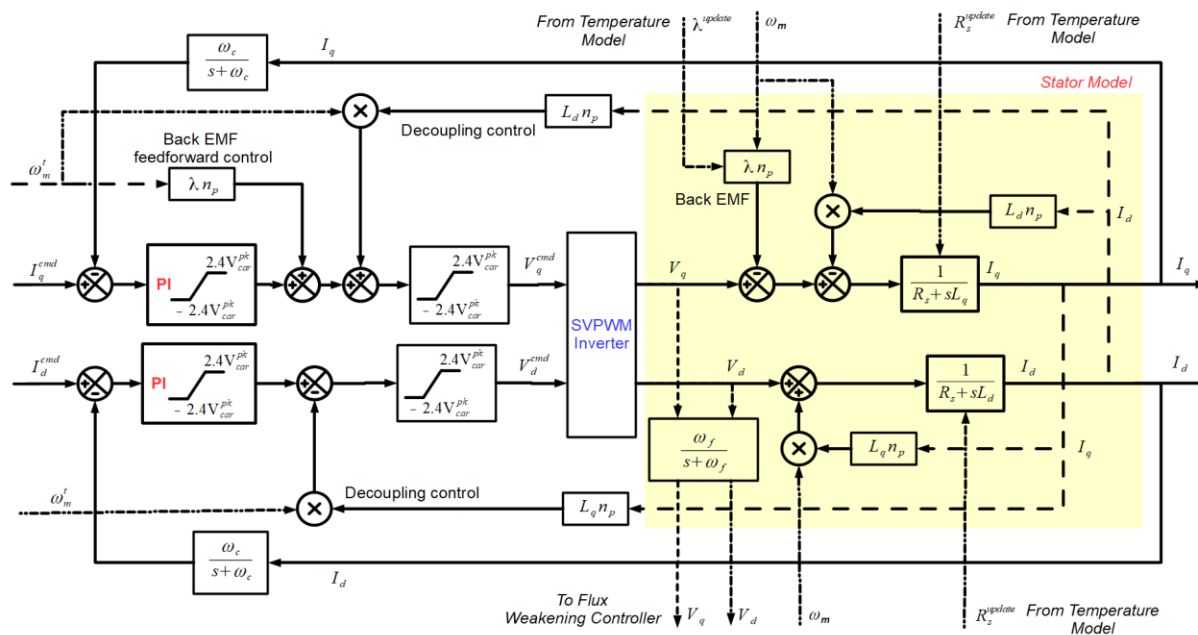
Abderrezak, A. and Madjid, K., "Sensor Fault Detection, Localization, and System Reconfiguration with a Sliding Mode Observer and Adaptive Threshold of PMSM"



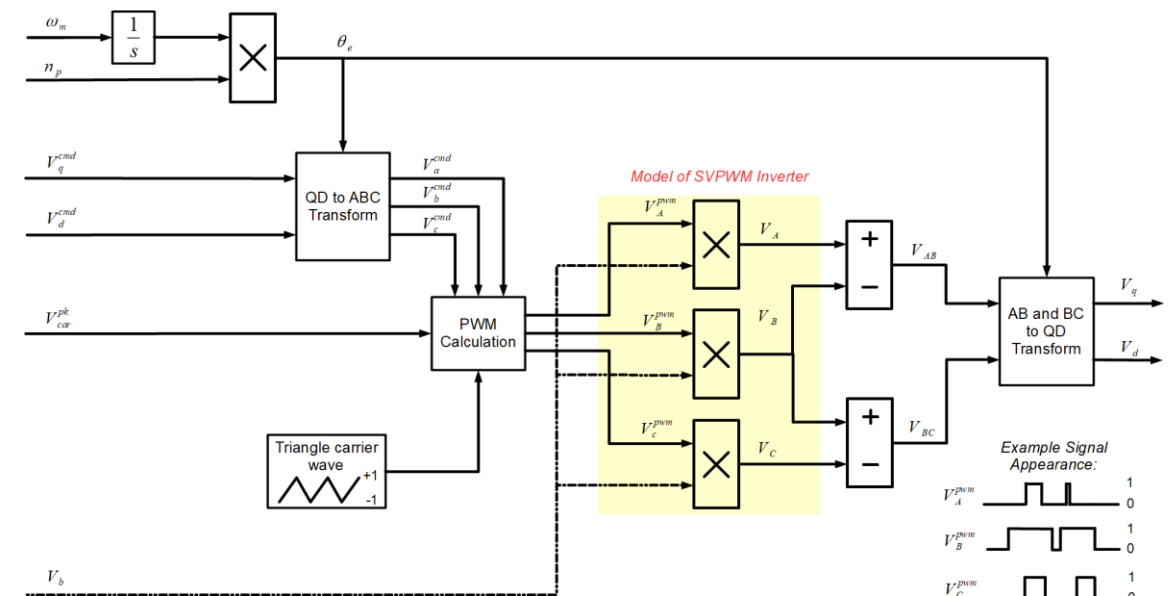
Stator, Inverter and Rotor Dynamics Modeling

- Field oriented control employed to maximize efficiency [1]
- Inverter modeled in ABC frame [2]
- Overmodulation of Space Vector Pulse Width Modulation (SVPWM) inverter is limited to 2.4
 - Nonlinear region

Model of PMSM Stator and Rotor



SVPWM Inverter Model



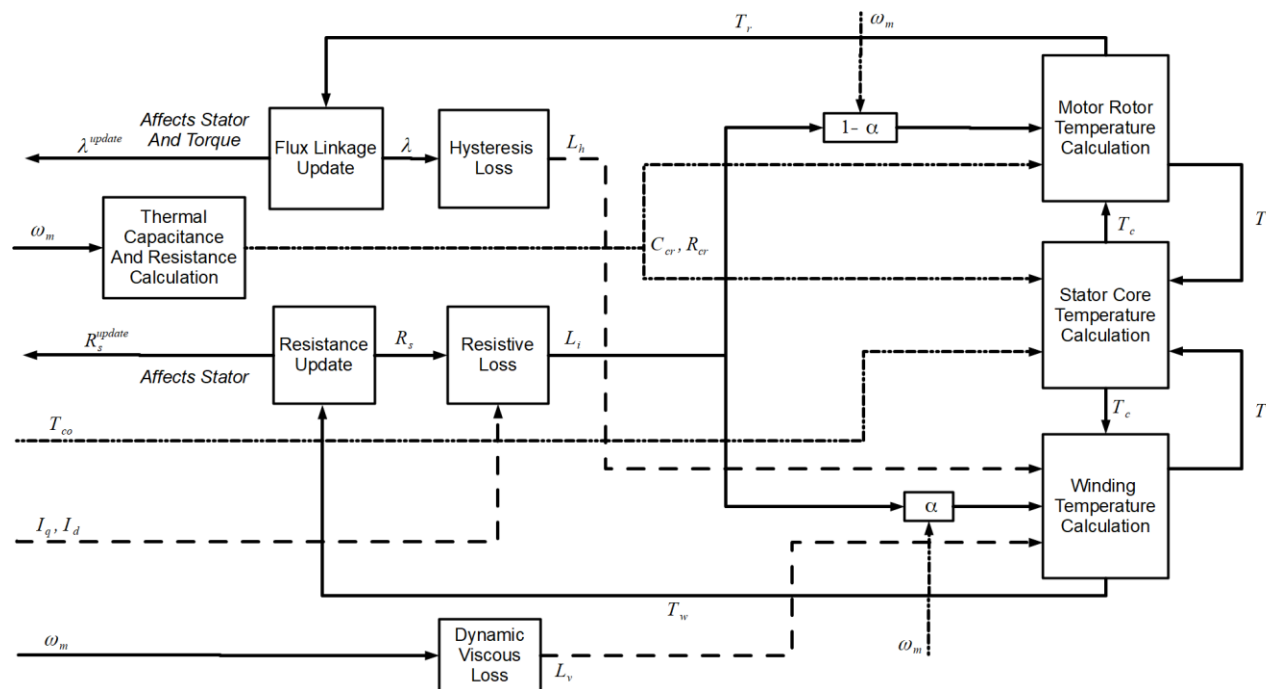
[1] Han, W. (2017), "Simulation Model Development of Electric Motor and Controller (Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden)," retrieved from <https://publications.lib.chalmers.se>.

[2] Panda, S, Mishra, A., Srinivas, B. (2009), "Control of Voltage Source Inverters using PWM/SVPWM for Adjustable Speed Drive Applications (Bachelors Thesis, National Institute of Technology Rourkela, Rourkela Odisha)," retrieved from <https://core.ac.uk/>

Motor Thermal Model

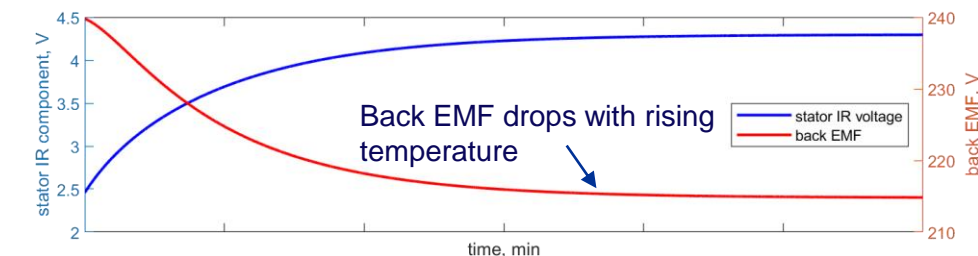
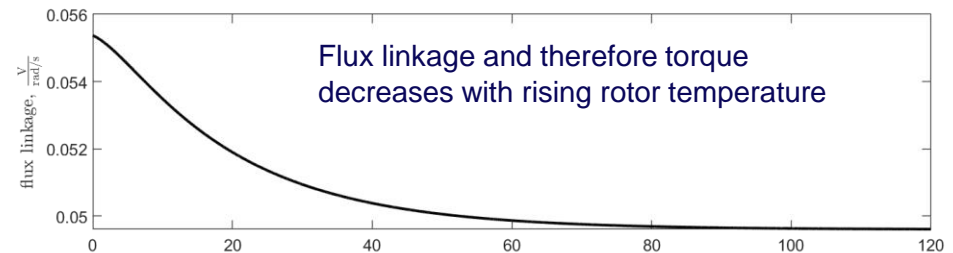
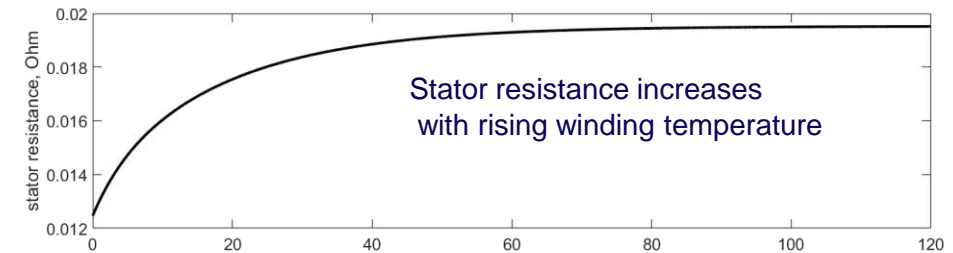
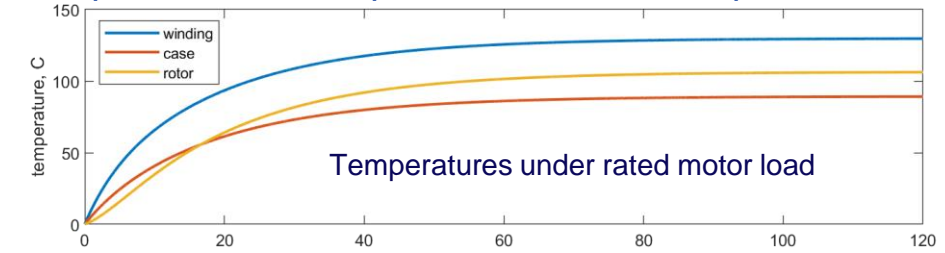
- PMSM thermal resistance and capacitance model [1]
- Approximations of heat transfer made among, cooling case, winding, rotor and stator core
- Captures temperature effect on resistance and flux linkage but not inductance

Motor Thermal Model



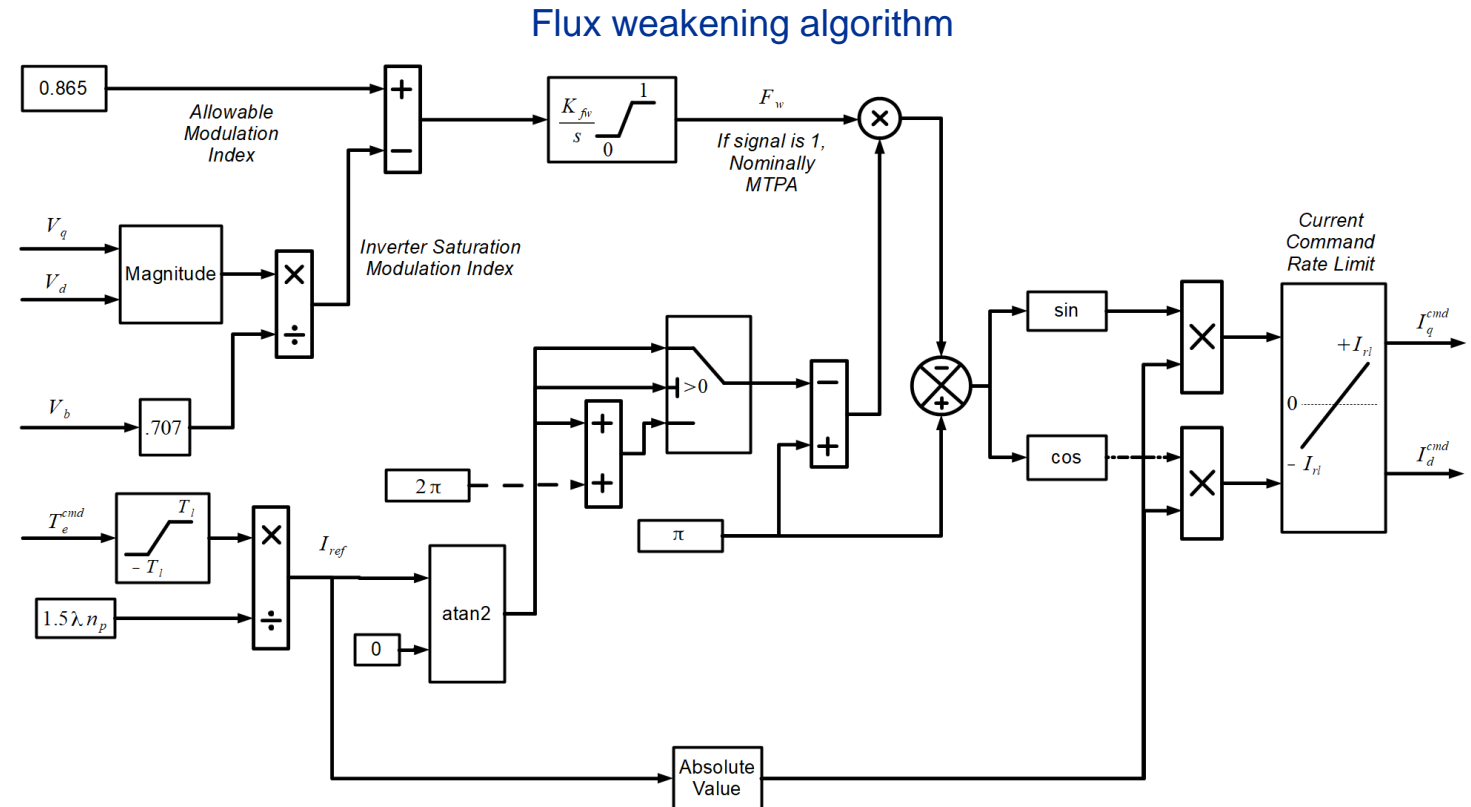
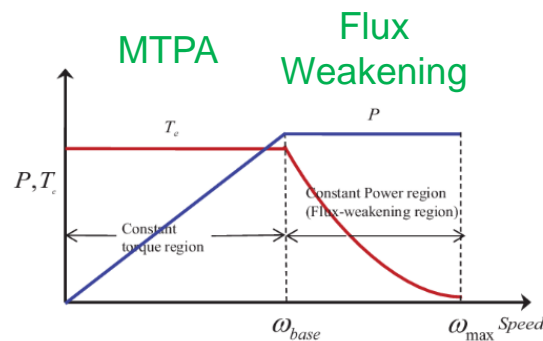
[1] Salyer, Z. (2019), "Thermal Models of Electric Powertrain Components for Cooling System Simulation and Design Requirements (Undergraduate Honors Thesis, The Ohio State University, Columbus, Ohio)," retrieved from <https://kb.osu.edu>

Temperatures of components under rated speed and load



Flux Weakening Control

- Flux weakening approach from a widely cited reference [1]
 - Reverts to max torque per amp (MTPA) control when not engaging flux weakening control

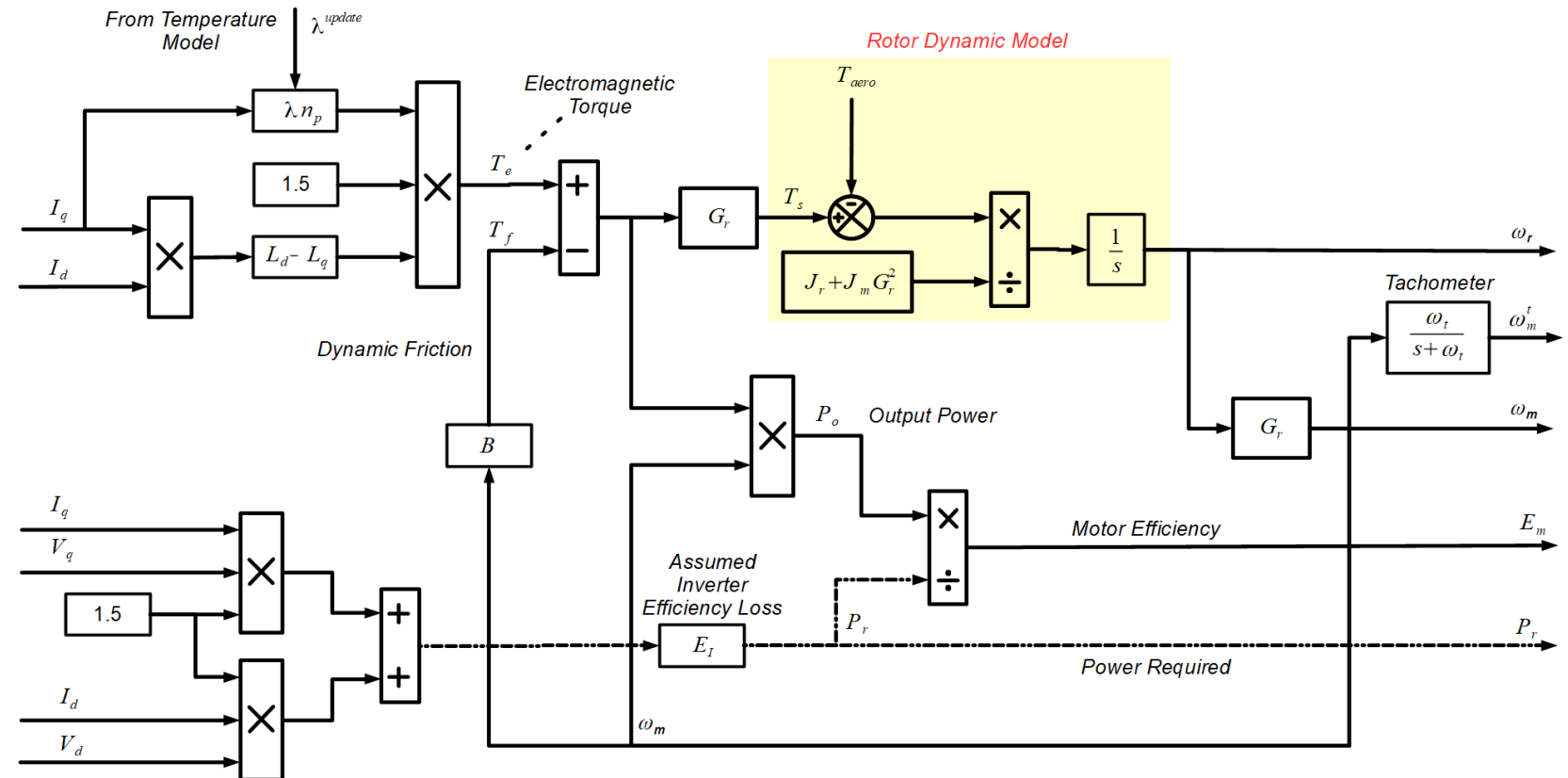


[1] J. Wait and T.M. Jahns, A New Control Technique for Achieving Wide Constant Power Speed Operation with an Interior PM Alternator Machine, Industry Applications Conference, 2001

Motor Torque and Rotor Dynamic Modeling

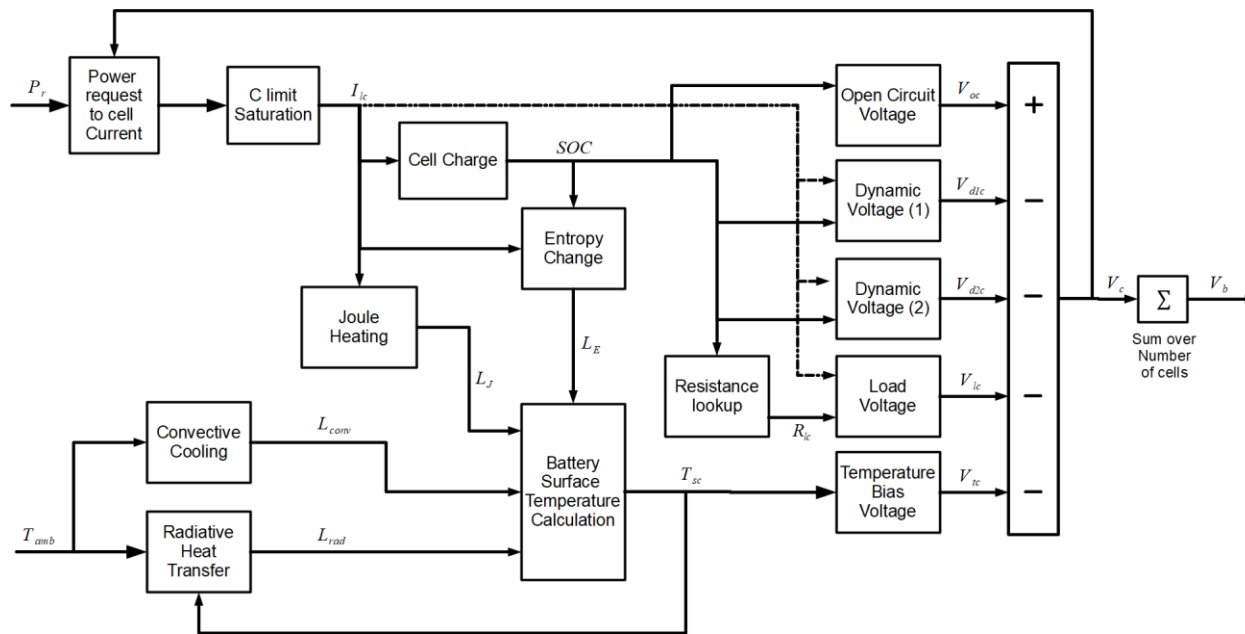
- Motor torque accounts for effects
 - Temperature
 - Dynamic Friction
- Motor speed assumed
 - Measured not estimated
 - Multiple of shaft speed by gear ratio

Motor Torque and Rotor Dynamic Model

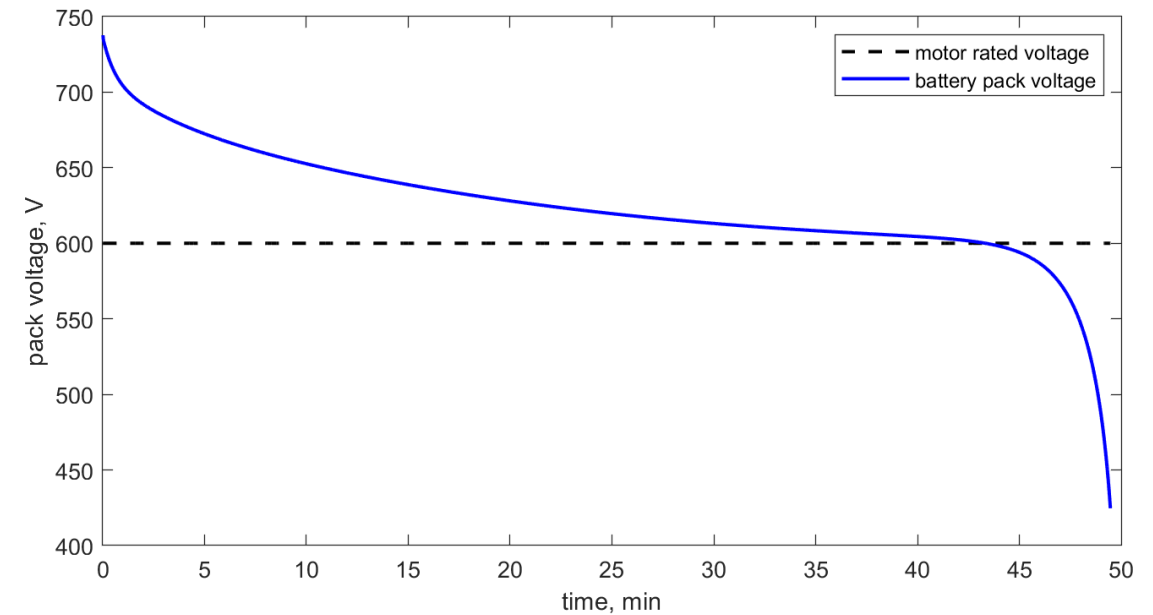


Battery Pack Model

- 18650 LiPo empirical equations [1][2]
 - Models voltage drops from static and dynamic loads
 - Assumed to be air cooled



Example sized battery under hover load



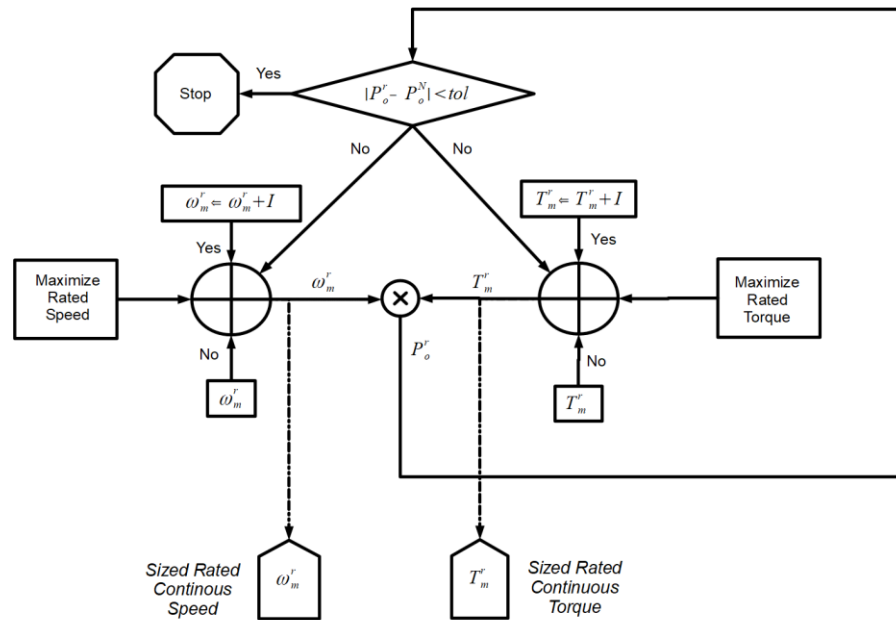
[1] Erdinc, O., Vural, B., and Uzunoglu, M., "A dynamic lithium-ion battery model considering the effects of temperature and capacity fading", In Proceedings of the 2009 International Conference on Clean Electrical Power, June 9-11, 2009, Capri, Italy, 2009.

[2] Shabani, B., and Biju, M., Theoretical Modelling Methods for Thermal Management of Batteries, Energies, Vol. 8, pp 10153-10177, 2015.

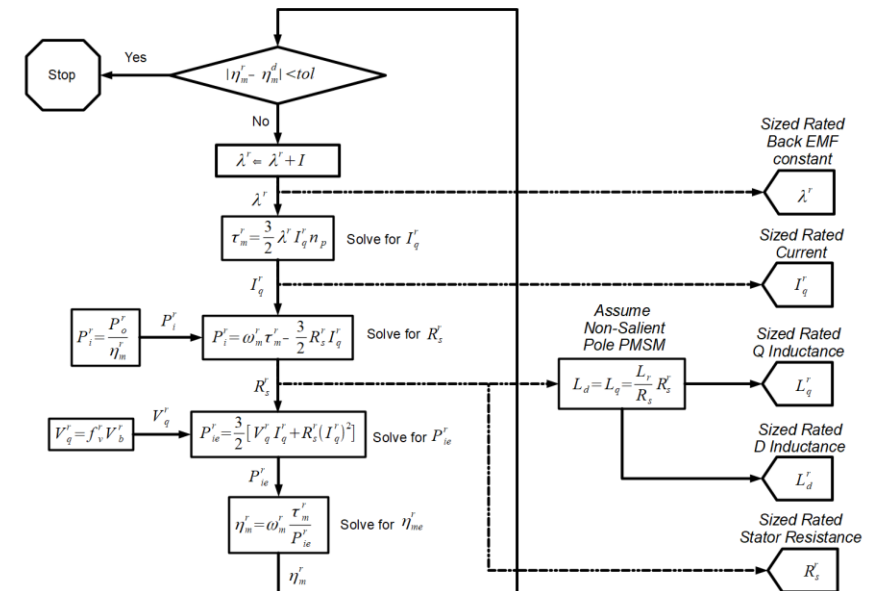
Motor Parameters Sizing Routine

- NDARC provides rated continuous power
 - For our purposes, flexibility to trade off speed and torque
 - Found beneficial for Lift plus Cruise to maximize rated speed
- Motor constants are sized once rated speed and torque are determined
 - Peak torque limit set as twice continuous torque

Rated Torque and Speed Sizing



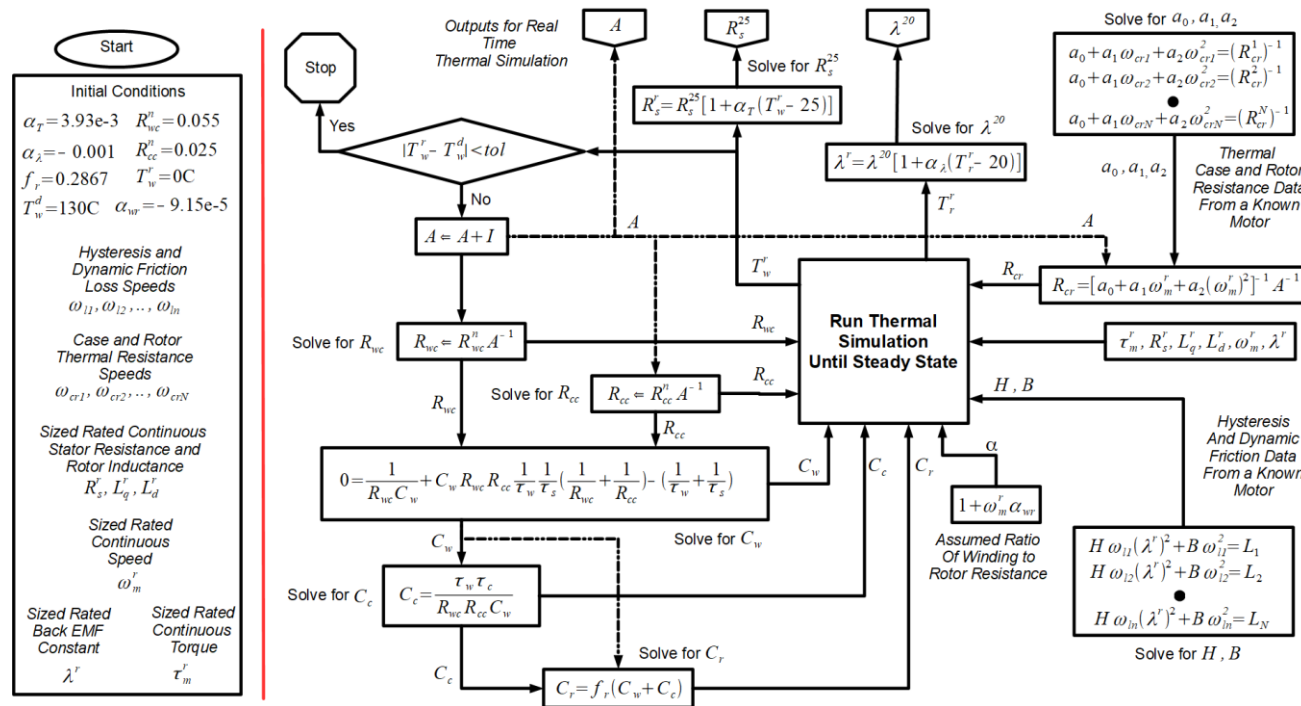
Motor Coefficients at Rated Condition Sizing



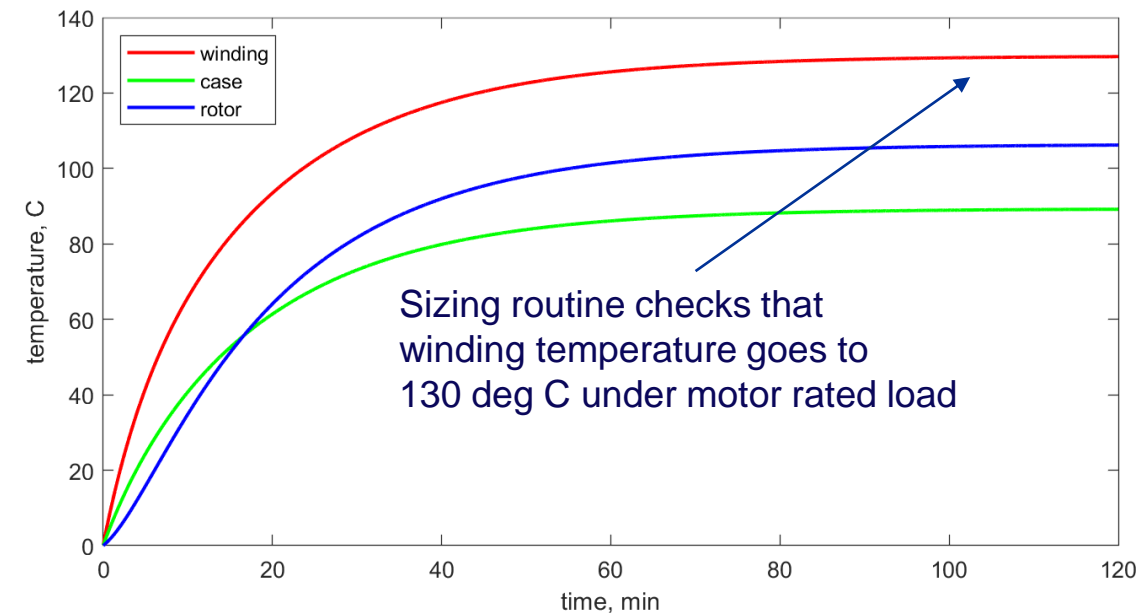
Motor Thermal Model Coefficient Sizing

- Experimental data [1]
 - Case and rotor resistance with speed
 - Hysteresis and dynamic friction with speed and flux linkage variation
- Compute stator resistance at 25 deg C and flux linkage at 20 deg C

Thermal Coefficient Hybrid Physics/Data Sizing Method



Thermal Performance under Rated Load/Speed

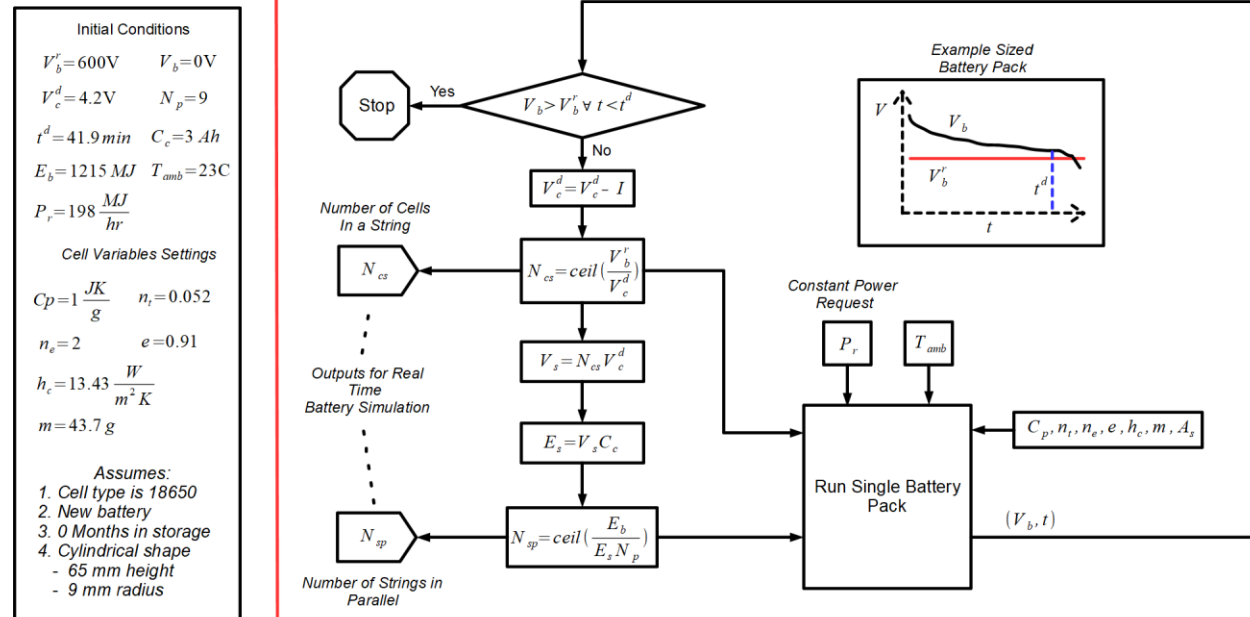


[1] Salyer, Z. (2019), "Thermal Models of Electric Powertrain Components for Cooling System Simulation and Design Requirements (Undergraduate Honors Thesis, The Ohio State University, Columbus, Ohio)," retrieved from <https://kb.osu.edu>

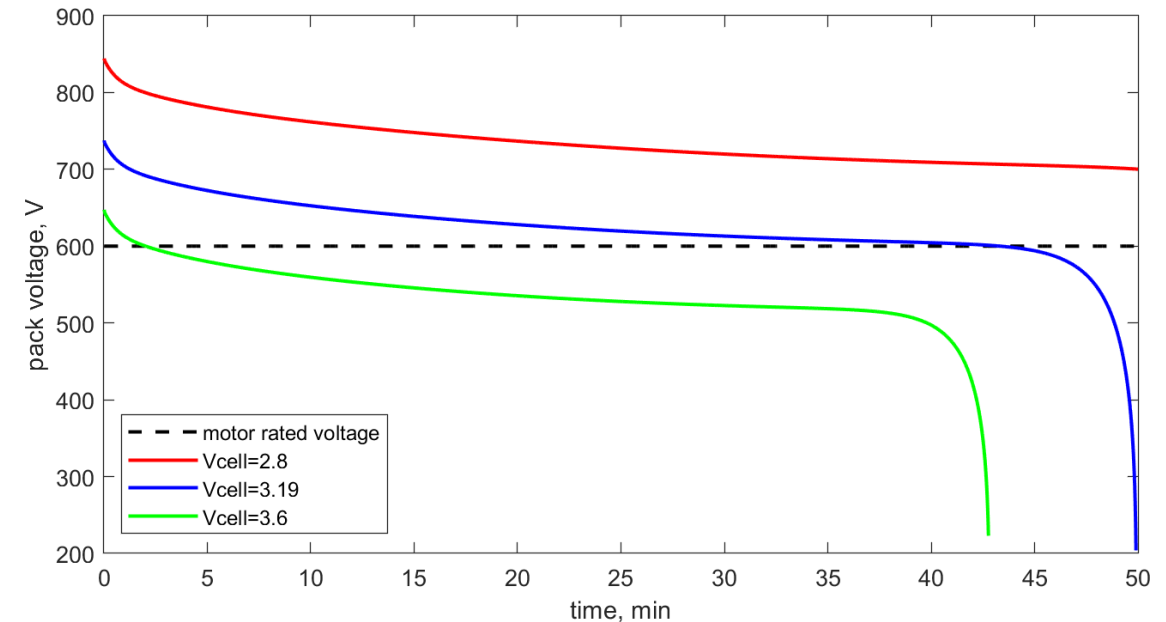
Battery Pack Sizing

- NDARC provides total mission energy for the vehicle
- The battery pack for each motor is sized iteratively so that voltages during the mission never drop below the motors rated DC voltage
 - In this case this requires battery voltage staying above 600V for 42 minutes while absorbing the hover design power load
 - The resulting cell voltage suggests whether it is a reasonable design

Battery Pack Sizing Algorithm

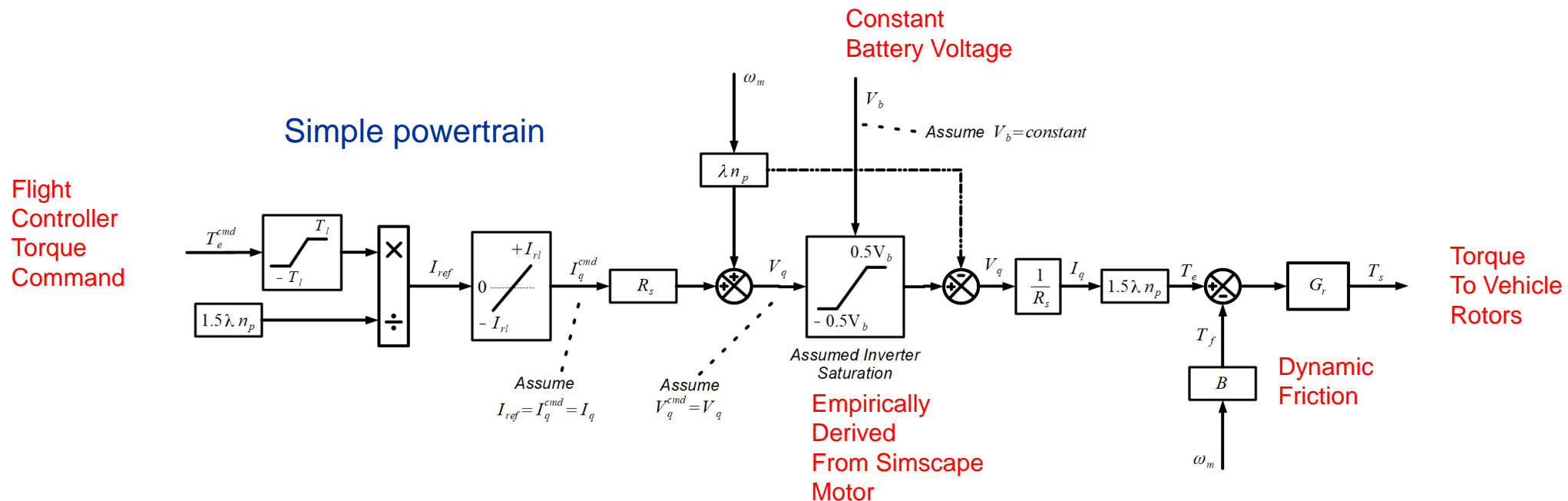


Example battery pack voltages for various cell voltages



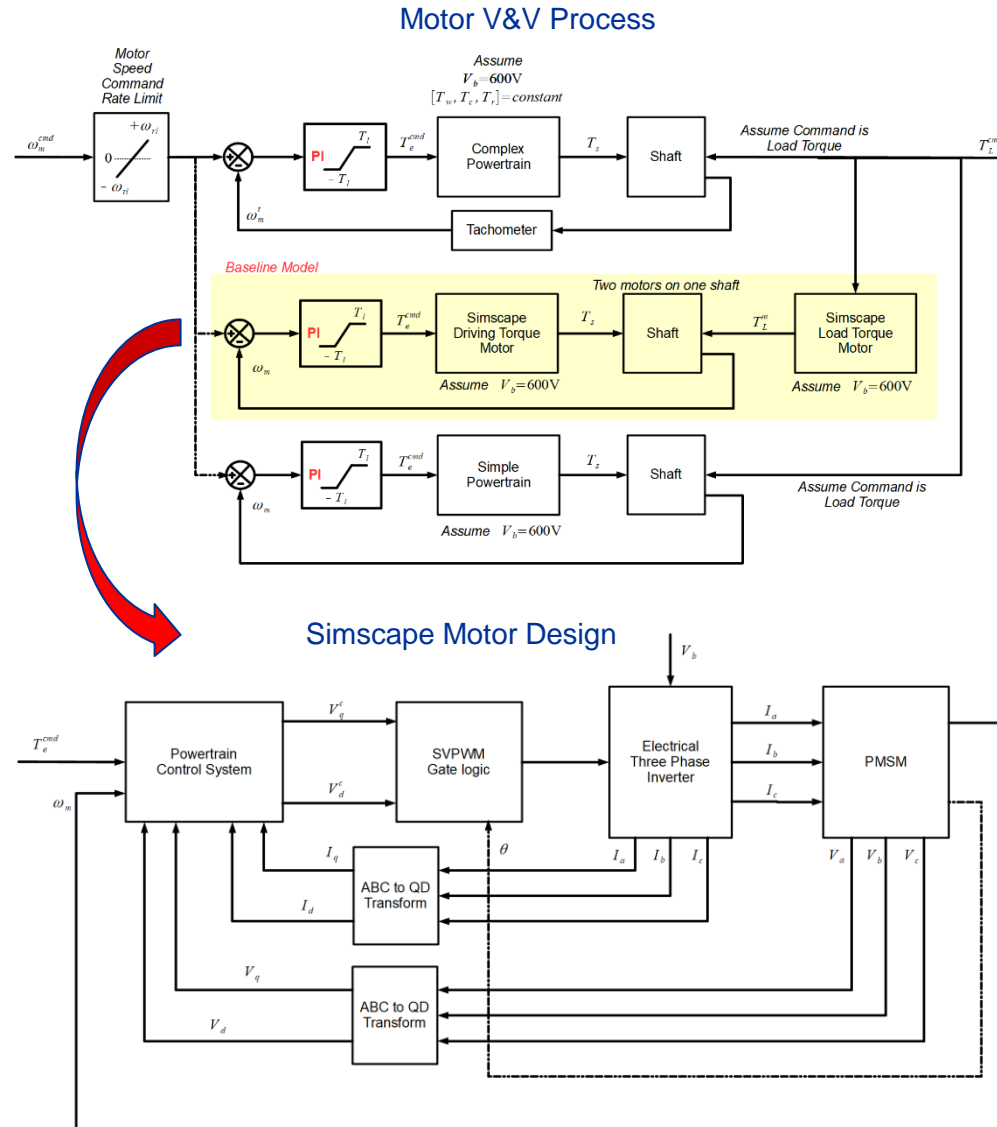
Simple Powertrain

- Assumptions to complex powertrain to capture dynamics within the rated envelope of the motor
 - Current reference is identically equal to current
 - Voltage command is identically equal to voltage
 - D-axis is assumed to not play a significant role in motor dynamics
 - Battery voltage can be assumed to be constant
 - Saturation limits and rate limits are preserved
 - Inverter is treated as a saturation block

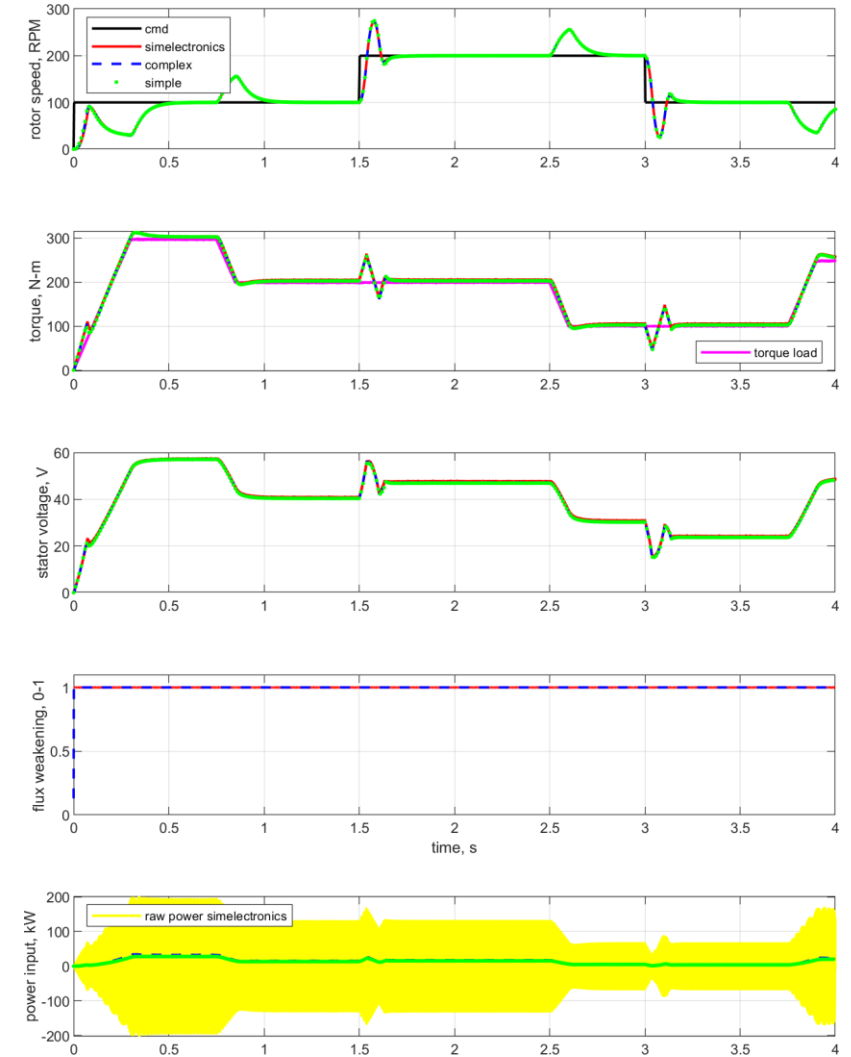


Low Speed Motor V&V with Simscape Model

- V&V against a representative powertrain model in Simscape (Provided by NASA Glenn)

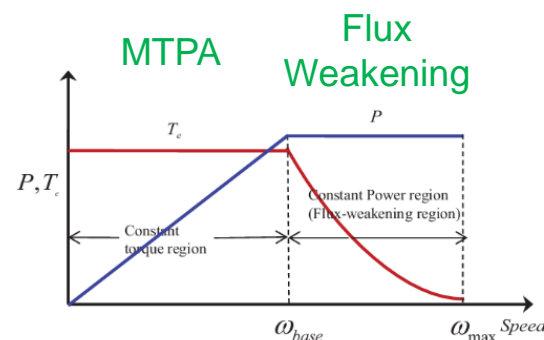


Operations within motor rated envelope

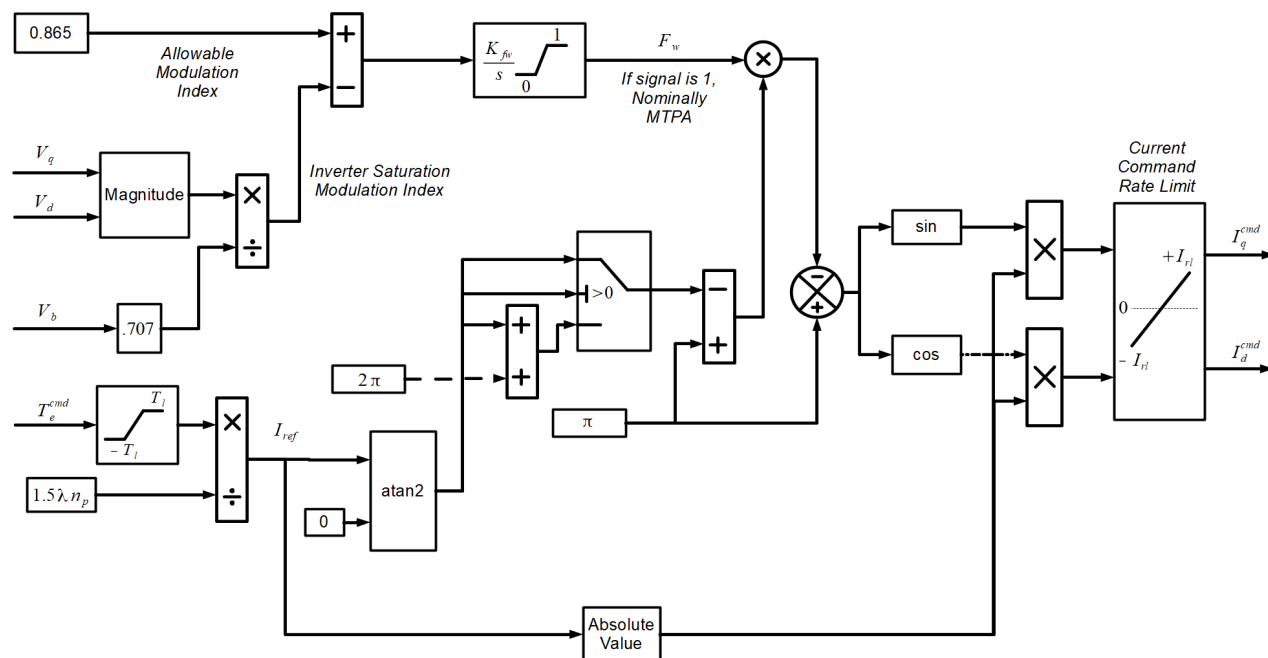


High Speed V&V and Flux Weakening Control

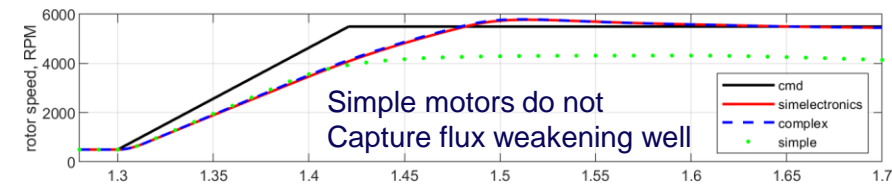
- Flux weakening approach from a widely cited reference [1]
 - Reverts to max torque per amp (MTPA) control when not engaging flux weakening control
 - Simple powertrain cannot capture dynamic effect of flux weakening as currently designed



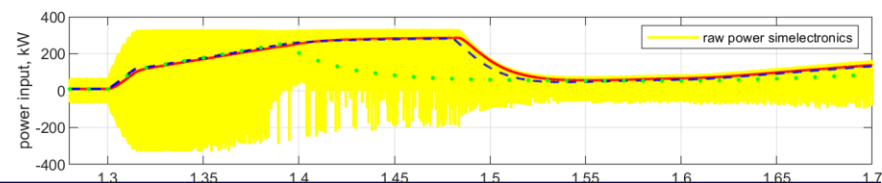
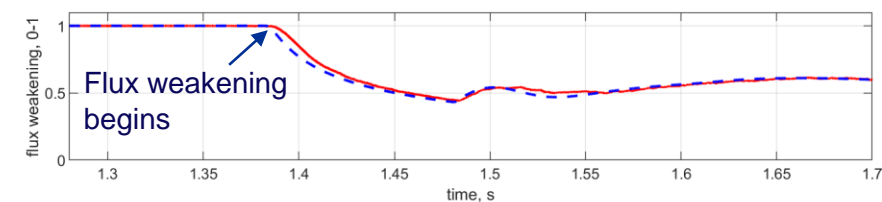
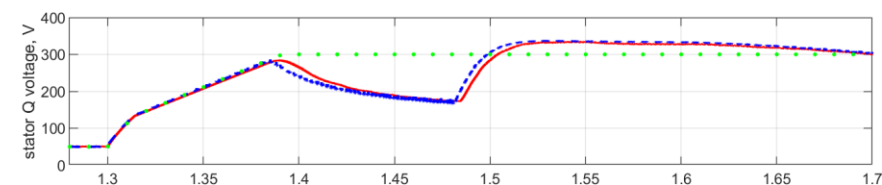
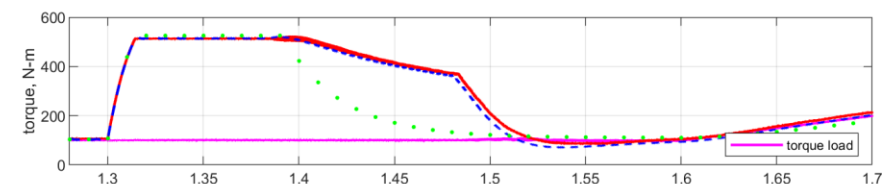
Flux weakening algorithm



Large RPM command with current rate limits removed



Simple motors do not
Capture flux weakening well



[1] J. Wait and T.M. Jahns, A New Control Technique for Achieving Wide Constant Power Speed Operation with an Interior PM Alternator Machine, Industry Applications Conference, 2001



Questions?